DESIGN AND ANALYSIS OF ELASTODYNAMIC LOCOMOTION FOR ROBOTIC INSECTS

Nicolae Lobontiu, Greg Fischer, M. Kurt Gordon,
Ephrahim Garcia, Michael Goldfarb
Vanderbilt University, Nashville TN 37235

One of the critical problems in the design of autonomous insect-like mobile structures is power consumption. The independent control of several legs is energetically expensive, while the energy capacity of typical electrochemical batteries is quite small. The net result is autonomous robotic insects that have extremely limited range. The authors propose an alternative approach to this problem that enables autonomous robotic insects to exhibit extremely high movement efficiency, and thus are capable of long range missions. Specifically, the desired limb motion is obtained by designing a lightly-damped skeletal structure and exciting the skeletal structure at an appropriate resonance. The approach is called elastodynamic locomotion. Rather than altering the open-loop dynamics of the machine, as is the case with conventional-scale machine control, the control actuator, a lead-zirconate-titinate piezoelectric material, serves only as an excitation source that excites the open-loop dynamics of the skeleton structure. Since the motion of the insect limbs operate at their structural resonance, the acceleration and deceleration for each motion (i.e.: stride for a walking machine) requires no power, which results in a highly efficient machine. Since the motion of the insect limbs is determined by design and not by control, the primary focus of this work is in the design of a skeletal structure that will exhibit walking motion when vibrationally excited. The paper presents some prototypes of insect designs that have generated a walking motion with minimal actuation. Also analyzed are the characteristic features of the gaits produced by each design. One prototype employs the sprawling gate exhibited by animals such as the salamander, gela monster, crocodile, etc. Other first-generation, non-biomimetic prototypes which use artificial gaits will provide baseline performance data for comparison to more advanced leg and skeleton designs which are currently under developement.

Presentation topics

- Concept of elastodynamic locomotion applied to robotic insects
- Robotic insect designs
  - Inchworm robotic insect
  - Quadruped robotic insect
  - Hexapod robotic insect
- Conclusions and further research

Design and Analysis of Elastodynamic Locomotion for Robotic Insects

Nicolae O. Lobontiu
Gregory Fischer
M. Kurt Gordon
Ephrahim Garcia
Michael Goldfarb

Design and Analysis of Elastodynamic Locomotion for Robotic Insects

Nicolae O. Lobontiu
Gregory Fischer
M. Kurt Gordon
Ephrahim Garcia
Michael Goldfarb

Advantages

- The power consumption is low due to excitation at resonance and the absence of control for individual joints
- The motion of elastic limbs is expected to be ample because of the peak resonant deformation
- The weight and complexity are minimum whereas the range and payload capacity are maximum
- No bearings are necessary because the exoskeleton moves by deformation which brings about mechanical robustness and immunity to environmental hazards
- There are no sensors and no control needed for locomotion which make the robotic insects robust to system-level failures
- The piezoelectric actuator confines requirements of motion generation within acceptable boundaries of sophistication
- The essential cost lies in design which is expected to produce all the capabilities necessary to intrinsic motion performance and control

Challenges

- Relative lack of significant experience base in the elastodynamic locomotion domain
- Difficulties from nonlinear behavior due to large deformations and possible chaotic response
- High sensitivity of the robotic structure to parameter deviation at resonance

Optimization Stages

Stage	Scope	Solution
Structural	Layout of a robotic insect • Topology • Shape • Sizing	Natural frequencies/mode shapes

Kinematic	• Interconnection between input (actuator) and output (limbs/robotic insect) motions
	• Motion amplification through:
	  • PZT actuator
	  • Kinematic linkages
		Geometry of mechanism motion

Dynamic	• Motion amplification through resonance • Damping (material, joints, ground contact) • Varying boundary conditions • Stability	Resonant dynamic motion of robotic insect

Robotic Insect Designs

General issues

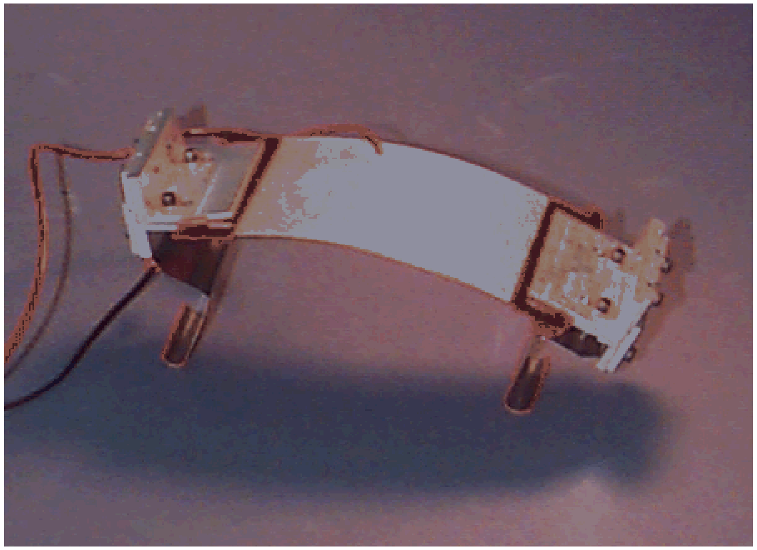
- The design approach to elastodynamic locomotion of robotic insect is a synthesis consisting of an identification/reduction sequence
- Acceptable designs will have to pass successively through several criterial layers, by satisfying corresponding requirements
- Classes can be thus identified until a group matching prescribed structural/functional criteria is identified
- The process would ask candidate designs exhibit class features such as:
    - Morphology/topology of design/actuation
    - Evidence of motion ability
    - Utilization of elastic components
    - Evidence of dynamic stability
    - Resonant behavior
    - Optimized response (maximum stride, minimum energy consumption, ability to change direction of motion)

Specific issues

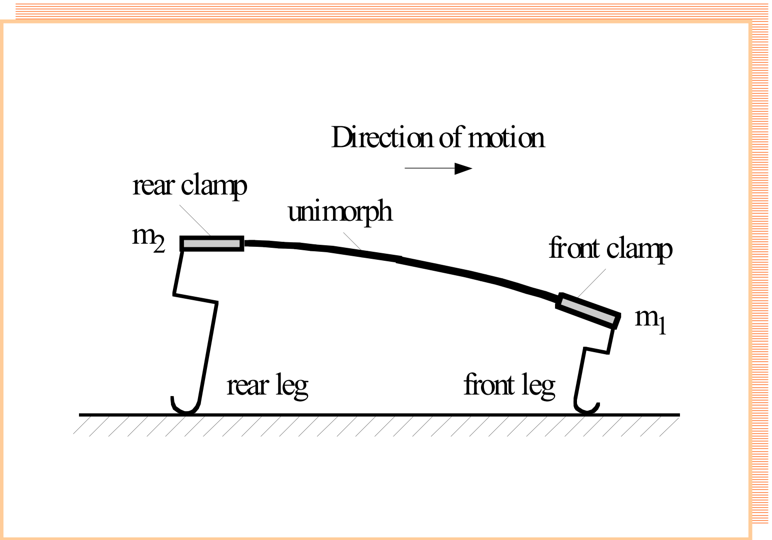
- Flexure hinges were used to allow controlled bending of limbs → friction and energy consumption minimization
- Motion amplification is needed since the piezoelectric source deformation is insufficient (lever-like limbs attached at points of actuator's maximum deformation)
- Design orientation to produce unidirectional motion but also provision for steering (right/left turning) capacity by altering the vibrational pattern of some limbs acting in unison at another resonant frequency, near the main one, or by matching local modes that would enable different pairs of legs to perform slightly-modified paths (simple variations in the input electrical signal)
- The designs are conceived to virtually permit the structure exhibit different gaits
- Modularity in the core structure allows economical and easy setup/testing of several configurations

Inchworm Robotic Insect

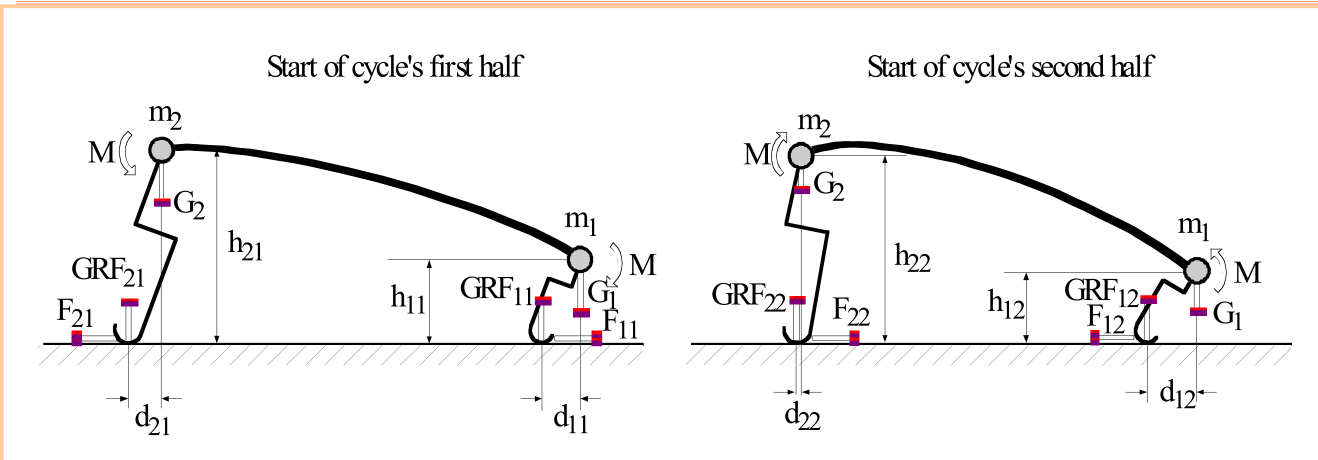
Actual design



Schematic



Simplified model



Bending moments

$$BM_{11} = M + GRF_{11} * d_{11} - F_{11} * h_{11} \quad (1)$$

$$BM_{21} = - M + GRF_{21} * d_{21} + F_{21} * h_{21} \quad (2)$$

$$BM_{12} = - M + GRF_{12} * d_{12} + F_{12} * h_{12} \quad (3)$$

$$BM_{22} = M + GRF_{22} * d_{22} - F_{22} * h_{22} \quad (4)$$

Rolling moments

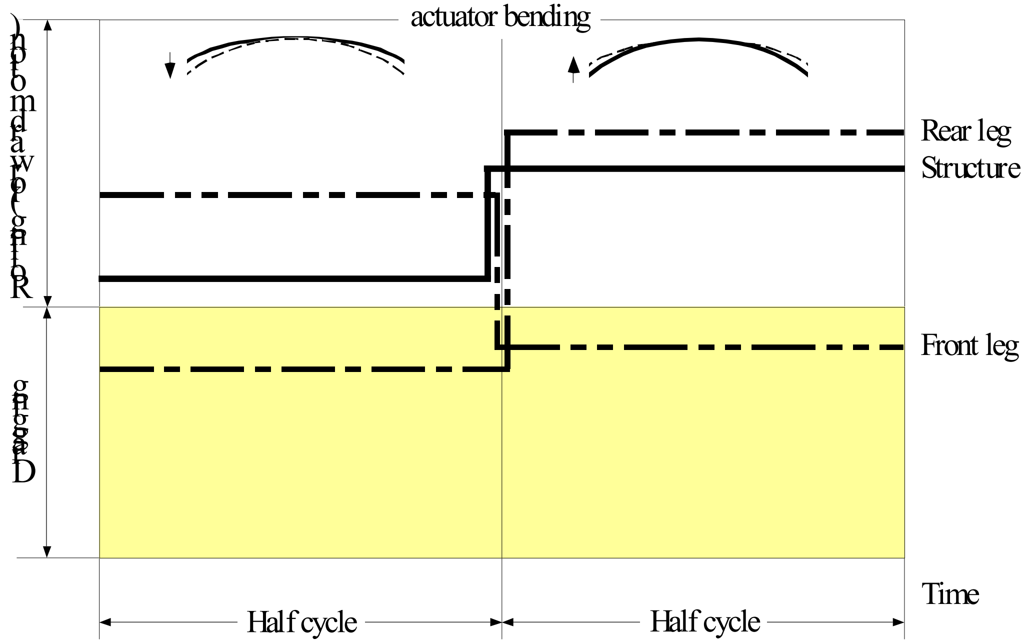
$$RM_{11} = M + G_1 * d_{11} \quad (5)$$

$$RM_{21} = - M + G_2 * d_{21} \quad (6)$$

$$RM_{12} = - M + G_1 * d_{12} \quad (7)$$

$$RM_{22} = M + G_2 * d_{22} \quad (8)$$

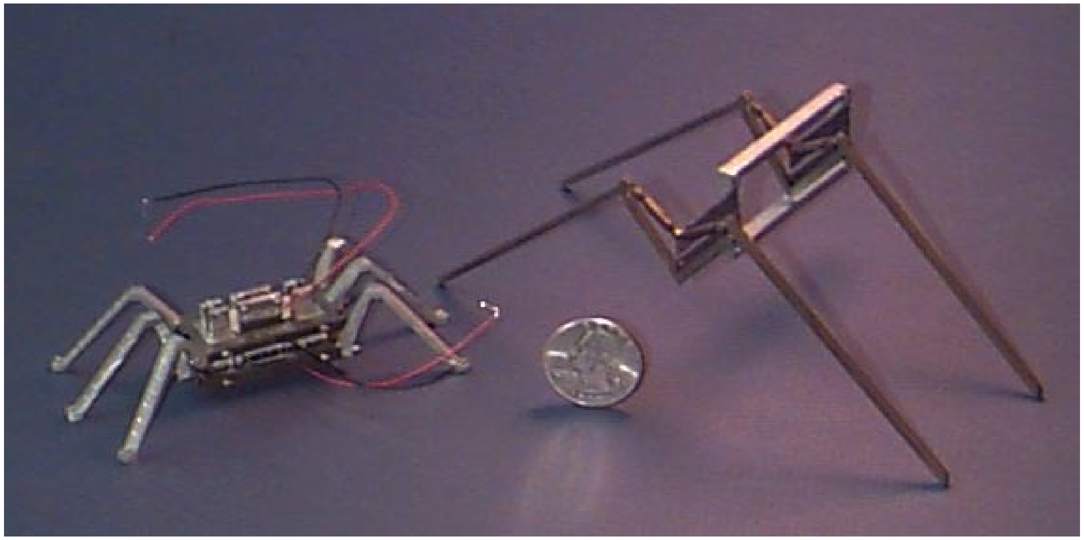
Motion diagram



- Unidirectional motion
- Two-segment cycle
- Inertia / ground reaction / friction / elastic compliance interaction
- Bending – rolling combination
- Legs perform different tasks and interchange roles during each motion segment

Quadruped and Hexapod Robotic Insects

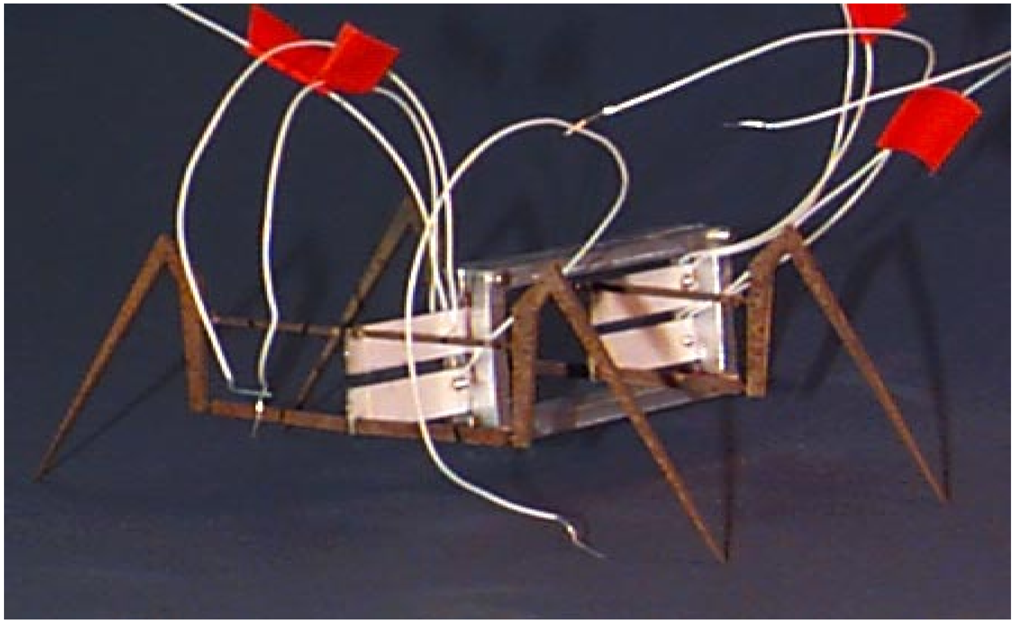
Actual designs



- Primary source of motion → bending vibrations produced by the piezoelectric actuators
- Exoskeleton → one or two frames where limbs are attached
- Limbs, that formally and functionally mimic insect legs, are provided with flexure hinges allowing performance of directionally-controlled bending and friction minimization
- Leg extremity follow a quasi-elliptical path which is necessary to support motion

Quadruped Robotic Insect

Actual design



- Four piezoelectric bimorphs drive two pairs of four-bar linkages
- Exoskeleton → one rigid frame
- Upper thigh of each linkage is pinned to top bimorph so that no moment can be transmitted
- Lower thigh of each linkage is cantilevered to bottom bimorph allowing moment transmission
- Exoskeleton and legs are capable of motion amplification
- Ninety degree phase difference in input signal between top and bottom bimorphs produce a trot gait

Concept of Elastodynamic Locomotion Applied to Robotic Insects

Design and analysis of lightly-damped skeletal structures (autonomous robotic insects) that are capable of motion when excited at a specific resonant frequency by minimum actuation from small-power motors, such as piezoelectric elements, without altering the open-loop dynamics of the whole structure

- **Transgression of the classical 'design-by-avoiding' principle that tends to keep operating structures away from their resonant states**
- **Structural-excitation compliance at resonance maximizes elastic deformation and minimizes energy consumption**

Concept of Elastodynamic Locomotion Applied to Robotic Insects

Design and analysis of lightly-damped skeletal structures (autonomous robotic insects) that are capable of motion when excited at a specific resonant frequency by minimum actuation from small-power motors, such as piezoelectric elements, without altering the open-loop dynamics of the whole structure

- **Transgression of the classical 'design-by-avoiding' principle that tends to keep operating structures away from their resonant states**
- **Structural-excitation compliance at resonance maximizes elastic deformation and minimizes energy consumption**